

GAMMA-RAY BURSTS AS A COSMIC WINDOW FOR GALAXY EVOLUTION

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Abstract: Present knowledge indicates that gamma-ray bursts are linked with massive stars. They will become invaluable probes of the early universe and galaxy formation. In the future, it will be possible to use gamma-ray bursts for two purposes: 1) to probe the history of massive star formation in the Universe by the rate of occurrence of gamma-ray bursts, and 2) for the study of galaxy evolution at all lookback times by determining the nature of the galaxy hosts. Because gamma-rays are not attenuated by intervening dust and gas, the selection of the cosmic sites of massive star formation by this method is less affected by the biases associated with optical-uv surveys (e.g. UV-dropout techniques). Infrared and sub-millimeter follow up studies of the hosts of gamma-ray bursts may: 1) reveal a putative population of reddened ($R - K \geq 4$) galaxies at high redshifts, and 2) detect very massive stars (population III) formed at $z \geq 5$.

Dusty starbursts and AGNs at high redshift

Optical surveys with the Hubble Space Telescope and large ground based telescopes have enabled in recent years the study of luminous UV galaxies out to redshifts $z \sim 4$ (Madan et al. 1996; Steidel et al. 1998). From the early analysis of galaxies in the HDF, Madan et al. (1996) concluded that there seemed to be little evidence for substantial amounts of dust obscuration in high redshift galaxies. It is remarkable how quickly this picture has changed after the recent deep field surveys in the mid-infrared, far-infrared, and submillimeter wavelengths (e.g. Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Blain et al. 1999; Elbaz et al. 1999). These new surveys have discovered a strongly evolving population of Luminous Infrared Galaxies (see Sanders & Mirabel 1996, for a review) that could be the progenitors of the present-day population of massive spheroidal galaxies.

The importance of dust at high redshifts has also been pointed out by Fabian (1999), who proposes a large population of dust enshrouded AGNs at $z > 1$ to account for the X-ray background. This prediction has recently been confirmed by the discovery with Chandra of a large population of X-ray point sources with “extremely faint, or in some cases undetectable” (i.e. $I > 26$) “optical counterparts” (Mushotzky et al. 2000). Furthermore, at millimeter and submillimeter wavelengths thermal emission from dust is currently detected from quasars up to redshifts of 5 (e.g. Omont et al. 1996; Carril et al. 2000). The implied far-infrared luminosities are $\gtrsim 10^{13} L_{\odot}$, dust masses $\gtrsim 10^8 M_{\odot}$, and molecular gas masses of a few $\times 10^{10} M_{\odot}$. These major events in galaxy evolution at high redshifts

are largely missed by UV/optical surveys, and it is now clear that the use of such surveys alone may lead to a substantial underestimate of the global star formation rate and certainly to a distorted picture of the early evolution of the most massive galaxies. What may be the fraction of massive star formation in the universe that occurred in galaxies so heavily obscured by dust that could not be detected in UV-selected surveys is an issue of current debate (e.g. Adelberger & Steidel 2000; Sanders 2000).

Gamma-ray bursts: A new cosmic window for galaxy evolution

Another major timely event in astrophysics has been the dramatic transformation in our understanding of gamma-ray bursts (GRBs). There is increasing evidence that the most common GRBs, those with durations longer than a few seconds, are at cosmological distances and are associated with sites of massive star formation. The physical properties of the afterglows, their locations at a few kpc from the center of host galaxies (e.g. Djorgovski 1999), and the statistics from the several thousands of GRBs detected so far with BATSE (Fishman et al. 1999), give strong support to the idea that the majority of GRBs are linked to the cataclysmic collapse of massive stars into black holes (Paczynski 1998; MacFayden & Woosley 1999). In this context, GRBs can be used as sign-posts to probe more accurately the history of massive star formation and galaxy evolution.

One of the great advantages of this approach is that GRBs can be detected at all lookback times. The broad band spectral and temporal behavior of the afterglows have confirmed that the bursts are beamed in relativistic jets, with the observer near the jet axis (Mészáros 1999; Kulkarni et al. 1999; Galama et al. 1999; Castro-Tirado et al. 1999). This leads to observed energies that are Doppler boosted by several orders of magnitude (Mirabel & Rodríguez 1999). Therefore, the detection of GRBs depends essentially on the beaming angle rather than on their distance, and they can be observed up to very large redshifts. An example of this was the optical afterglow of GRB990123, which could be seen with a simple pair of binoculars, since it reached an optical brightness of 8.6 mag, despite the fact that it came from $z=1.6$. High resolution spectroscopy of such optically bright bursts, which are many magnitudes brighter than quasars at the same redshift, could be very valuable to probe with unprecedented sensitivity the Ly α forest, and consequently, the chemical evolution of the universe.

The nine GRBs with redshifts determined by *optical* techniques prior to the end of 1999 are in the redshift range $z = 0.43 - 3.47$, with a mean of $z = 1.3$ (see also Blain & Natarajan 1999). However, this mean redshift is almost certainly biased toward low values because sources at very early epochs appear rather red and it is difficult to determine their redshifts by optical observations alone. For instance, no [OIII] or Ly α lines from objects at $1.3 \leq z \leq 2.5$ can be seen in the optical. Furthermore, there are several GRB afterglows that appeared to be extremely red whose redshifts are unknown. Some of these could be related to the death of a putative class of Population III stars, which are very massive stars brought on by cooling of molecular hydrogen in the dark ages of the very high redshift universe, before galaxies were formed (Lamb & Reichart 1999; Bromm, Coppi & Larson 1999). One of the best cases to explore this possibility is GRB980329, for which Fruchter (1999) hypothesized $z \geq 5$.

Dust obscuration is very important in studies of recently formed compact objects (e.g. Mirabel et al. 1999). Because GRBs are the last phase of the evolution of the

most massive stars (Woosley 1999) which do not live long enough to leave their place of birth, it is expected that a large fraction will be still enshrouded in their placental clouds of molecular gas and dust. The observations of GRB afterglows are consistent with this picture: 1) among the 47 X-ray afterglows with good localizations, *about half* had no optical counterparts (Greiner 1999), 2) despite persistent optical follow ups, three radio afterglows without optical counterparts have been detected, and 3) some afterglows appear to be extremely reddened (e.g. GRB990705). Dust obscuration is the most likely reason for the non detection of optical transients. Indeed the absence of detectable optical flux accompanying strong X-ray emission in the 1-60 keV energy band of SAX may simply be due to the strong redshift dependence of dust obscuration at optical wavelengths in comparison to the X-rays, i.e. $\tau_{\text{opt}}/\tau_{\text{X-ray}} \propto (1+z)^4$ (Taylor et al. 1998). Therefore, GRBs can be used to detect a putative population of dust-enshrouded forming galaxies at high redshifts.

The future

After the breakthrough produced by the X-ray satellite Beppo-SAX (Costa et al. 1997), it is expected that in the coming years, high energy space missions (SAX, HETE2, CHANDRA, XMM, INTEGRAL and SWIFT) will be providing about 50 GRB X-ray afterglows per year with localizations in the range of 1 arcsec to 1 arcmin. Furthermore, the localizations of the gamma-ray bursts can be improved a posteriori using the Interplanetary Network.

We note that the selection of the initial sample of star-formation sites in this approach is less affected by the problems and biases associated with the optical-UV selections of star formation sites, which are strongly influenced by reddening effects. Indeed the gamma rays are not attenuated by the intervening columns of gas and dust. The bursts thus provide an unbiased sampling of cosmic sites of massive star-formation.

An important caveat is that most X-ray afterglows until now have had error boxes of a few arcmin², a region large enough to contain from tens up to a few hundred galaxies, therefore it is very difficult without afterglow detections in the optical, infrared or radio wavelengths to identify unambiguously which object is the host of the GRB. However, the science programs of the recently launched Chandra and XMM, which carry sophisticated grazing incidence mirrors mounted aboard sophisticated satellites, include ToO observations of X-ray GRB afterglows with subarcminute error boxes. These X-ray telescopes can provide X-ray positions with arcsecond error boxes. A case in point is the recent Chandra observation of GRB000210 on the basis of the sole GRB error box provided by the Beppo-SAX wide field camera (Garcia et al. 2000 in GCN 544).

Studies of the galaxy hosts of GRBs with future instruments (e.g. SIRTf, FIRST, NGST, ALMA, etc) will open a new cosmic window for galaxy formation and evolution.

Conclusion

Gamma-ray bursts can be used as beacons to:

- 1) study the history of massive star formation in the universe,
- 2) to detect the putative population III stars at redshifts ≥ 5 ,
- 3) to detect a population of dust-enshrouded massive galaxies in formation,
- 4) to determine the chemical evolution of the universe.

Besides large optical telescopes, this approach will require infrared and sub-millimeter instruments of unprecedented sensitivity.

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